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DEVELOPMENT OF RESPONSE SURFACE REGRESSION MODEL FOR OPTIMIZING WEAR RATE OF BORON STEEL

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Abstract

Prediction of wear rate of boron steel (50B50) influenced by a combination of three factors namely applied load, hardness and peening intensity, was attempted by developing a second order response surface regression model. In the developed model, the influencing factors like peening intensity, applied load, second degree polynomial of peening intensity and interactions of applied load with both of hardness and peening intensity were having significant effect on influencing the abrasive wear rate of boron steel. But the interaction between hardness and peening intensity produced a non-significant effect on wear rate. Based on the Tukey's test and grouping of the levels of different factors, the minimum wear rate of inter-critically annealed boron steel with hardness value of 446 Hv was observed after shot peening at 0.17 Almen "A" with an applied load of 75N.

Keywords: Response surface regression, Load, Hardness, Peening intensity, Abrasive wear

1. INTRODUCTION

Boron steel with medium carbon content has widely been used in various agricultural engineering applications because of its low cost as well as good mechanical and tribological properties obtained through bulk and surface treatments. Soil engaging components of agricultural implements such as rotavator blades, cultivator sweep, shovel etc. are subjected to severe abrasion and fatigue due to unforeseen and unpredictable load in actual field condition. Low maintenance cost and enhanced service life are further needed in case of agricultural implements as they lead to less fuel consumption, less changeover time and uniformity in operation for obtaining more yields (Ferguson *et al*., 1998).Therefore, various researchers attempted bulk and surface treatments like heat-treatments (Singh *et al*., 2008, 2010, 2011), nitriding (Moore, 1975), carbonitriding (Moore, 1975), boriding (Er U and Par B, 2006), shot peening (Singh *et al*., 2008, 2010, 2011) and other procedures for preventing various wear modes such as adhesive, tribochemical, fatigue abrasive and erosive wear in soil working components. Resistance to abrasive wear in metals generally depends on composition (Ueda *et al*.,2002), microstructure of the materials (Modi, 2007), surface properties (Singh *et al*.,2010), applied load (Singh *et al*.,2008), sliding distance (Singh *et al*., 2008, 2010), hardness (Khrushchov,1974) of the meeting surfaces and abrasive particle size (Modi, 2007).The other parameters affecting the abrasive wear are speed, temperature, presence of foreign particles and environmental condition (Wirojanupatump and Shipway, 2000) etc. The rate of decrease in wear rate with surface hardness depends upon the microstructure and mechanical properties of the metal. Shot peening, an inexpensive and trustworthy technique was also carried out to enhance the service life of agricultural machinery components (Singh *et al*., 2010). It effectively introduces the high compressive stresses at the specimens' surface, refined the microstructure and improves the surface

hardness; all these factors lead to improve the abrasive wear resistance of steels. Therefore, modifying the microstructure and enhancing the hardness through heat treatment processes and surface modifications by means of shot peening application under different load conditions may be implemented to reduce the three body abrasive wear. However, identification of optimum combinations of such factors plays a crucial role in bringing down the cost of application and improving the efficiency of procedure. This can be achieved through appropriate modelling techniques.

Response surface regression is a well-known statistical modelling technique to optimize the response of the dependent variable based on the independent factors (Khuri and Cornell, 1996). A lot of studies have been done by numerous researchers to optimize the response variable by using response surface regression. Sivasakthivel *et al.* (2010) predicted tool wear from machining parameters by using response surface methodology. Tsao (2009) adopted grey Taguchi method to optimize the milling parameters of aluminum alloy with multiple performance characteristics and Abhang and Hameedullah (2010) presented a power prediction model for turning EN-31 steel using response surface methodology. This model further recommended to be used in the automotive industries for deciding the cutting parameters for minimum power consumption (Ginta *et al.*, 2009).With this, the present study was undertaken to develop a mathematical model to optimize the wear rate of boron steel (50B50) based on hardness, peening intensity and load using response surface regression analysis (RSRA).

2. METHODOLOGY

Chemical composition of test material (50B50, Boron steel) in weight percentage was 0.50% C, 0.21% Si, 0.78% Mn, 0.95% Cr, 0.005% B and remaining Fe. This steel was undergone under three different types of heat-treatment cycles for obtaining different levels of hardness. The hardness and microstructure of control (untreated) and heat-treated specimens were measured by Vicker's hardness tester and Scanning Electron Microscope (SEM) respectively as per standard procedure. The shot peening was carried out on polished steel specimens at 0.17 A to 0.47 A peening intensities on Mech Shot, Jodhpur, India make shot-peening machine at CIAE, Bhopal. Standard "A" type Almen strips were used to calibrate the peening intensity. The expose time was varied, keeping other parameters constant, for obtaining variation in peening intensities from 0.17 A to 0.47A. Low stress abrasive wear in dry sand was measured as per ASTM G-65 standard using DUCOM, Bangalore, India make rubber wheel abrasion tester. The specimens were tested at three loads i.e. 75, 200 and 375Newton.

To evaluate the effect of hardness, peening intensity and load on wear rate of boron steel, a three factor experiment was conducted in completely randomized design to get a total of 60 treatment combinations consisting of three levels of load, four levels of hardness and five levels of peening intensity. Response surface regression analysis (RSRA) is the most apt technique to develop a mathematical model for a dependent variable in terms of quantitatively measured input factors, especially for data generated from a factorial design structure. Thus, in the present study, response surface regression analysis was used to optimize the wear rate of boron steel based on different levels of load, hardness and peening

intensity. So, wear rate (Y) can be mathematically represented as a function of load (X_1), hardness (X_2) and peening intensity (X_3). Mathematically, this can be expressed as,

$$\text{Wear rate, } Y = f(X_{iu}) + e_u, \qquad (i=1, 2, 3\ldots\ldots n)$$

Where 'f' represents response surface regression function, e_u= residual term, and X_{iu} is the level of the i^{th} factor combination in the u^{th} observation.

The second order response surface design was used to approximate the mathematical function of 'f', especially when the functional form is unknown. Thus, in the present study following second order response surface regression model was used to optimize the wear rate of boron steel in terms of load, hardness and peening intensity.

$$Y_u = \beta_0 + \beta_i X_{iu} + \beta_{ii} X_{iu}^2 + \beta_{ij} X_i X_j + e_u, i < j \cdots\cdots\cdots (1)$$

Where, u = 1, 2, ……n represents the 'n' observations and x_{iu} is the level of the i^{th} factor combination obtained from3 levels of load, 4 levels of hardness and 5 levels of peening intensity in the u^{th} observation. The parameters were estimated through the method of least squares and $b_0, b_i's, b_{ii}'s, b_{ij}'s$ were denoted the best linear unbiased estimate of $\beta_0, \beta_i's, \beta_{ii}'s, \beta_{ij}'s$ respectively.

Once the model was developed, ridge analysis also performed to optimize the wear rate of boron steel in terms of load, hardness and peening intensity. The goodness of fit of the model also checked using coefficient of determination (R^2) and Root mean square error (RMSE).All the statistical analysis was performed using SAS 9.2.

3. RESULTS

The microstructure of as received (Control) and annealed (AN) specimen was found to be almost similar. The percentage of ferrite was observed 5% more in AN as compared to control specimen. The inter-critically annealed (ICA) and quenched and tempered (QT) specimen were depicting mixture of tempered martensite (80%) with ferrite (20%) and tempered martensitic (95%) with 5% retained austenite respectively. The hardness of the ICA and QT specimens was more than twice the hardness of control and annealed steels because; ICA and QT specimens had martensitic structure, which is harder than ferritic and pearlitic structure (Table 1).

Table 1: Parameters affecting the wear rate

Heat-treatment processes	As received	Annealed	Inter-critically annealed	Quenched and tempered
Microstructure	85% pearlite and 15% ferrite	80% pearlite and 20% ferrite	80% martensite and 20% ferrite	95% tempered martensite and 5% retained austenite
Hardness (Hv) (four levels)	180	170	446	458
Peening intensity (Almen "A") (five levels)	0.0, 0.17, 0.27, 0.37 and 0.47	0.0, 0.17, 0.27, 0.37 and 0.47	0.0, 0.17, 0.27, 0.37 and 0.47	0.0, 0.17, 0.27, 0.37 and 0.47
Load applied (N)	75, 200 and 375	75, 200 and 375	75, 200 and 375	75, 200 and 375

(three levels)				

The wear rate of heat-treated peened and un-peened specimens monotonically decreased with sliding distance because of the work hardening due to continuous plastic deformation. In un-peened condition, the wear rate of control and annealed specimens were almost same (Figure 1). Whereas, in the case of ICA and QT specimens, the wear rate were considerably less than that of AN and control specimens because of formation of dual phase ferrite-martensitic structure or tempered martensitic structures, respectively, which offer superior combination of mechanical properties (like hardness strength and toughness) primarily required to resist the abrasive wear. The wear rate in annealed specimens reduced considerably as compared to control specimen, when the specimen was subjected to low peening intensity of 0.17Almen “A”. This may be attributed to greater work hardening effect, improved toughness, more harmonized structure, lack of pre-processed residual stresses or flaws, higher ductility in annealed specimens as compared to untreated one. Greater ductility and lower hardness level of again assisted the entrapment of fine abrasives and holdings of wear debris for longer period. The wear rate was again noted to be decreased considerably in case of ICA and QT specimens, as compared to untreated specimen. In general, for all specimens the wear rate decreased with peening intensities, up to 0.17Almen “A”. But the wear rate again increased with increase in peening intensity beyond this limit. Thus, the peening intensity should be restricted up to 0.17Almen “A” for achieving the minimum wear rate. The wear rate of QT and ICA specimens were comparable and significantly lower than control and annealed specimens.

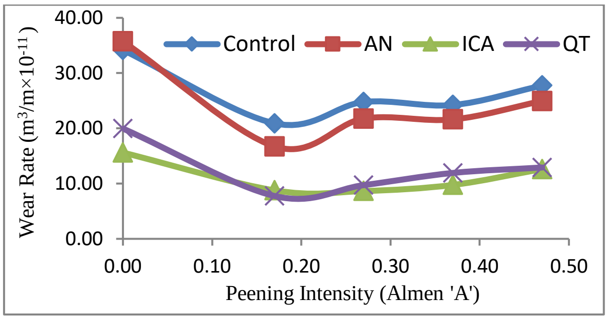

Fig. 1 Wear rate of boron steel at different peening intensities.

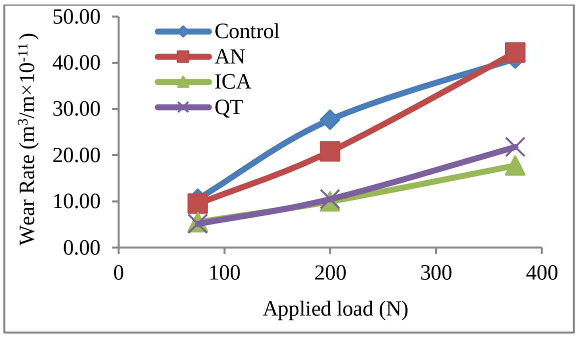

Fig. 2 Wear rate of boron steel at different applied loads.

Similarly, it was observed that the wear rate increases with increase in applied load for all type of heat-treatments (Figure 2). This result indicates that the wear rate of control with annealed specimens and ICA with QT specimen were comparable. It was further noted that wear rate of was observed that the wear rate (at lower applied load of 75 N) of annealed and control were almost the same. Similar trend was noted for ICA and QT when these were compared. At intermediate load (200N), annealed specimens exhibited lower wear rate as compared to control specimen due to the work hardening of sub-surface. Additionally, at lower applied load, mainly rolling and pitting types wear associated with rubbing type of wear mechanism was prevailing. Here, hardness, and work-hardening of subsurface or micro-structural changes did not play any significant role. At higher applied load, mainly cutting

and ploughing type of wear is prevailing where hardness of the surface played an important role. At intermediate load both cutting and ploughing along with rubbing type of wear mechanism are prevailing. Here, work-hardening of the subsurface, surface hardness, toughness of the materials play role to control the wear. As a result at intermediate load, annealed specimen exhibited improved wear resistance than control specimen.

A second order response surface regression model was developed to optimize the wear rate of boron steel in terms of load, hardness and peening intensity. It was observed that only five explanatory variables namely, applied load, peening intensity, second degree polynomial of peening intensity and interactions of applied load with both of hardness and peening intensity were having significant influences on wear rate of boron steel. Rest of the variables as well as constant intercept had insignificant influence. Though, the fitted mathematical form of the equation was significant with sufficiently high R^2 value (0.88) but the developed regression model was not found suitable for sufficiently accurate prediction of abrasive wear in boron steel due to high significance for lack of fit (Table 2). The reason behind this may be attributed to the closeness of the model where prediction will be possible only within the given range of experimental parameters.

Table 2: Regression analysis of Boron steel

Particulars	Estimated value	Coefficient of multiple determination (R^2)	F-value for model	F-value for lack of fit
Intercept	5.17^{ns}	0.88	90.93^{***}	444.95^{***}
Load	0.16^{***}			
Hardness	0.02^{ns}			
Peening intensity	-76.91^{***}			
Load x Load	0.31×10^{-6ns}			
Hardness x Hardness	$-0.50 \times 10^{-4\ ns}$			
Peening intensity x Peening intensity	151.13^{***}			
Load x Hardness	$-0.20 \times 10^{-3***}$			
Load x Peening intensity	-0.06^{***}			
Hardness x Peening intensity	0.02^{ns}			

***- Significant at 1% level, ns – Not significant

The regression analysis concealed that linear, quadratic and interaction effect of input factors found to have significant effect on wear rate (Table 3).However, due to highly linear influence of load on wear rate, the linear components of the model were the major contributors to the total explained variations in the dependent variable. The linear or direct effect of load produced significant influence on wear rate; whereas, the other two variables hardness and peening intensity produced a non-significant and significant effect, respectively. Only the quadratic effect of peening intensity was significant on wear rate at 1% level of significance. The interaction between load with hardness and load with peening intensity

produced significant decrease in wear rate. But the interaction between hardness and peening intensity produced a non-significant increase in the wear rate.

Table 3: Contribution of components of model in regression analysis on R^2

Regression	Degree of Freedom	R-Square	F-Value
Linear	3	0.74	350.29^{***}
Quadratic	3	0.07	33.13^{***}
Cross product	3	0.07	34.25^{***}
Total Model	9	0.88	139.23^{***}

The contour region of wear rate for the interaction effect of input factors was depicted in figures 3, 4 and 5 to analyze the cause- effect relationship. The interactions between all the factors were analyzed through contour graph and following conclusions were drawn.

Tukey's HSD tests for selection of optimum combination of factors

The following table describes the procedures for selection of combination of factors responsible for lowest abrasive wear in boron steel. It can be emphatically stated that intercritically annealed boron steal with hardness value of 446 Hv subjected to shot peening at an intensity of 0.17 Almen "A" under an applied load of 75 Newton exhibits the maximum wear resistance against three body abrasive wear.

Table 4: Tukey's minimum significance difference and grouping for factors

Name of factors	Level of factors	Mean wear rate	M.S.D. at 5%	Tukey's Grouping
Load in Newton	75	7.66	0.82	C
	200	17.23		B
	375	30.65		A
Heat treatment with Hardness in Hv	Control (180)	26.36	1.04	A
	Annealed (170)	24.16		B
	Intercritically annealed (446)	11.08		D
	Quenched and tempered (458)	12.45		C
Peening intensity in Almen "A"	0.00	26.37	1.23	A
	0.17	13.54		D
	0.27	16.23		C
	0.37	16.88		C
	0.47	19.56		B

Mean value with same letter for Tukey's grouping are not significantly different.

4. CONCLUSIONS

The wear rate of boron steel was steadily increasing with the increase in the applied load, but the same was decreased sharply on peening intensity of 0.17 Almen "A" and the gradually increasing beyond this level. Hardness of the material under study had a negative effect on wear rate but due to change in microstructure, it showed a fluctuating trend within a localized range. The minimum wear rate was achieved by load at 75N, hardness at 446 HV obtained by intercritically annealing the boron steel and peening intensity at 0.17 Almen "A". The interaction between load with hardness and load with peening intensity was significantly influencing the wear rate. But the interaction between hardness and peening intensity results into a non-significant increase in the wear rate.

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